

Improving photovoltaic efficiency: a systematic study of P&O and INC MPPT techniques

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ABSTRACT

Achieving high efficiency in photovoltaic (PV) systems under fluctuating irradiance and temperature conditions relies on effective maximum power point tracking (MPPT) techniques. Among the most commonly adopted approaches, perturb and observe (P&O) and incremental conductance (INC) are favored for their ease of implementation and operational flexibility. Nevertheless, a systematic comparison of their performance under dynamic conditions remains limited. This study conducts a comparative evaluation of P&O and INC algorithms using MATLAB/Simulink, with emphasis on tracking accuracy, convergence speed, and overall efficiency. A standard PV module is exposed to rapid variations in irradiance and temperature to examine algorithm robustness. The results indicate that although P&O achieves fast convergence in steady-state operation, it exhibits noticeable oscillations around the maximum power point, resulting in efficiency losses of up to 3%. Conversely, the INC method offers improved tracking precision and reduced oscillations, yielding efficiency gains of 2–4% over P&O in dynamic environments. These findings underline the trade-off between algorithmic simplicity and tracking accuracy, and provide practical guidance for selecting MPPT strategies in both grid-connected and standalone PV applications.

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1. INTRODUCTION

The growing adoption of renewable energy sources presents an effective solution to climate change, primarily because of their low levels of greenhouse gas emissions. Among these, solar power emerges as a widely recognized and abundant renewable energy source [1]. Solar energy systems encompass technologies that convert solar heat or light into usable energy forms [2]. These technologies primarily fall into two categories: solar photovoltaic (PV) systems, which convert sunlight into direct current electricity using semiconductors, and solar thermal systems, which harness solar heat for heating or electricity production [3]. Over the past decade, intelligent maximum power point tracking (MPPT) techniques such as fuzzy logic controllers, artificial neural networks (ANN), and adaptive neuro-fuzzy inference systems (ANFIS) have demonstrated significant potential in improving photovoltaic system performance under dynamic environmental conditions [4]. However, these methods often involve high computational complexity and require extensive parameter tuning or training [5], which may limit their practical real-time application [6]. In this context, the present study offers a systematic comparative simulation of conventional MPPT algorithms,

namely perturb and observe (P&O) [7] and incremental conductance (INC) [8], under various environmental conditions and PV configurations, providing insights into their efficiency, stability, and dynamic response [9]. This approach not only serves as a benchmark for future hybrid or intelligent MPPT designs but also highlights the novelty of the work in terms of simulation scope and PV system configuration, which has not been comprehensively addressed in previous studies [10], [11].

Although photovoltaic solar panels are increasingly efficient and adaptable across various voltage and current outputs, they exhibit substantial variability in energy production and can only deliver peak power under specific voltage and current conditions, influenced by factors such as weather variations, temperature, and shading [12]. To address these challenges, the supervision of energy performance through MPPT algorithms becomes crucial, aiming to maximize power generation while minimizing energy losses [4], [7].

In recent years, the development of intelligent MPPT techniques such as fuzzy logic, neural networks, and adaptive control has shown significant potential in improving the dynamic performance of photovoltaic systems [13], [14]. These approaches are capable of handling non-linearities and sudden environmental variations more efficiently than conventional algorithms [15]. Nevertheless, their implementation remains challenging due to higher computational requirements, complexity of tuning, and limited feasibility for real-time embedded applications [14]. Therefore, it remains essential to conduct a systematic investigation of traditional methods like perturb and observe (P&O) and INC, which, despite their simplicity, can be optimized to achieve high efficiency and stability [16]. Additionally, exploring their potential hybridization and suitability for real-time operation may provide a promising pathway toward more practical and adaptive PV control strategies [17]. The maximum power point (MPP) represents the optimal operational state at which a PV module generates its highest power output, characterized by specific voltage and current values [18]. This point shifts in response to weather conditions (such as illumination and temperature) and load variations [19], [20]. Achieving maximum power extraction requires the implementation of a control strategy referred to as maximum power point tracking, which continuously locates the point of optimal energy output [21]. Consequently, numerous studies have focused on developing algorithms to optimize the performance of photovoltaic systems, including methods like Hill-Climbing, P&O [22], and incremental conductance.

This work investigates a simulated photovoltaic system controlled using perturb and observe and Incremental Conductance MPPT algorithms. A boost-type DC–DC converter is integrated within the configuration due to its superior performance in MPPT applications and its ability to efficiently align the impedance between the PV array and the electrical load [23], [24]. Table 1 presents a summary of the most widely utilized traditional MPPT methods applied in PV systems. These approaches are particularly appreciated for their straightforward design, ease of implementation, and minimal computational requirements. However, they vary in terms of tracking precision, transient response and adaptability to fluctuating environmental conditions. Conversely, Table 2 summarizes the principal hybrid and intelligent MPPT strategies proposed for PV systems. These approaches integrate traditional algorithms with artificial intelligence or optimization mechanisms to enhance tracking accuracy and dynamic response.

Table 1. Comparative summary of conventional MPPT strategies and their main attribute

Technique	Description
Constant voltage (CV)	Maintains PV voltage at a fixed fraction of the open-circuit voltage as an MPP approximation.
Open-circuit voltage (OCV)	Estimates MPP voltage as a proportion of the measured open-circuit voltage.
Short-circuit current (SCC)	Sets operating current as a defined ratio of the short-circuit current.
Hill climbing (HC)	It updates the converter duty ratio according to the gradient of the power–voltage (P–V) characteristic.
Load current (LC)	Matches PV current with the load demand to maintain near-optimal operation.
Ripple correlation control (RCC)	Uses correlation of voltage/current ripples with power variations for adaptive duty cycle control.

Despite the broad coverage of MPPT approaches in the literature, only a limited number of studies offer a direct comparison between the conventional P&O and INC algorithms under the same dynamic irradiance and load conditions, particularly for large-scale photovoltaic systems. Many previous works emphasize intelligent MPPT approaches or investigate traditional methods individually, which limits fair performance benchmarking. In this context, the present study conducts a controlled comparative evaluation of P&O and INC MPPT algorithms using MATLAB/Simulink. The contributions of this work include a comparative assessment under steady-state and rapidly changing environmental conditions, a quantitative analysis of convergence speed, oscillatory behavior, and energy efficiency using identical system parameters, and an evaluation of the practical applicability of each algorithm in both standalone and grid-connected photovoltaic systems.

The manuscript is structured into four main parts as shown in Figure 1: i) Section 1 presents the mathematical model of the PV array; ii) Section 2 describes the DC–DC converter; iii) Section 3 details the implementation of the two MPPT algorithms considered; and iv) Section 4 reports and discusses the simulation outcomes, ending with the main findings.

Table 2. Intelligent and hybrid MPPT algorithms for PV applications

Technique	Description
Adaptive neuro-fuzzy inference system (ANFIS)	Integrates neural networks and fuzzy logic to adaptively model nonlinear relations for optimal MPPT control.
Fuzzy logic–P&O hybrid	Combines fuzzy inference with the P&O algorithm to reduce oscillations and enhance tracking precision.
Fuzzy logic–INC hybrid	Employs neural prediction with the INC algorithm for improved accuracy and faster MPP convergence.
Genetic algorithm (GA)–fuzzy logic control (FLC)	Utilizes genetic optimization to auto-tune fuzzy parameters, enhancing system adaptability.
ANFIS–particle swarm optimization (PSO)	Improves ANFIS by optimizing membership and learning parameters via PSO.
Hybrid swarm intelligence methods	Merges swarm-based approaches (e.g., PSO, ACO) to achieve robust and adaptive tracking under dynamic conditions.

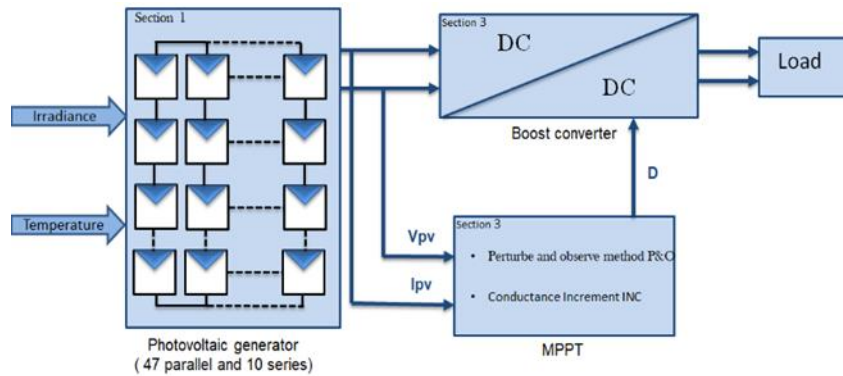


Figure 1. Schematic diagram of adaptation by MPPT control

2. METHOD

This section describes the overall methodology used to model the PV system and to assess the performance of the MPPT algorithms. In order to ensure clarity, reproducibility, and scientific rigor, the PV module characteristics, simulation parameters, and control strategies are systematically described, followed by a clear explanation of how each MPPT algorithm handles tracking speed, steady-state oscillations, and tracking accuracy.

2.1. Mathematical modeling of the PV model

The basic element of a photovoltaic module is the solar cell, which can be modeled as a current source generating a photocurrent (I_{ph}) directly related to the incident solar irradiance. This current source is connected in parallel with a diode that represents the electrical characteristics of the P–N junction [25]. Consequently, the PV module is depicted as illustrated in Figure 2, with corresponding equations provided below. The mathematical expression governing the current–voltage characteristics of a PV module is provided in (1), as outlined in [19].

$$I = N_p \cdot I_{ph} - N_p \cdot I_0 \left[\exp \left(\frac{q \left(\frac{V}{N_s} + \frac{I R_s}{N_p} \right)}{K A T} \right) - 1 \right] - \frac{\left(\frac{N_p \cdot V}{N_s} + I R_s \right)}{R_{sh}} \quad (1)$$

The generated photocurrent I_{ph} varies primarily with solar irradiance and cell temperature, and is given by (2).

$$I_{ph} = [I_{sc} + K_i \cdot (T_0 - T_{ref})] - \frac{G}{G_{ref}} \quad (2)$$

The short-circuit current (I_{sc}) at standard test conditions (STC), corresponds to the highest current the photovoltaic module can deliver when the output terminals are directly connected. These conditions are defined with a reference cell temperature (T_{ref}) of 25 °C, corresponding to 298 Kelvin (K). The solar irradiance (G) at STC is set at 1000 W/m², marked as G_{ref} . Additionally, K_i is denoted as 0.005254 (A/°C). The parameter I_0 , known as the saturation current, varies with cell temperature and is defined by (3) [25].

$$I_0 = I_{rs} \left(\frac{T_0}{T_{ref}} \right)^3 \cdot \exp \left(\frac{q \cdot E_g \left(\frac{1}{T_{ref}} - \frac{1}{T_0} \right)}{K A} \right) \quad (3)$$

The reverse saturation current (I_{rs}) represents the cell's leakage current under standard temperature and irradiance conditions (T_{ref} , A). The silicon band gap energy ($E_g=1.1\text{eV}$) is adopted as in [19]. The corresponding (I_{rs}) is computed using (4).

$$I_{rs} = \frac{I_{sc}}{\exp \left(\frac{q \cdot V_{oc}}{N_s A K T_0} \right) - 1} \quad (4)$$

For simulation purposes, the 1STH-215-P PV module is selected as the reference model. The PV array consists of 47 parallel strings, each containing 10 series-connected modules. The electrical parameters of the 1STH-215-P module under STC, serving as the basis for subsequent modeling and analysis, are summarized in Table 3.

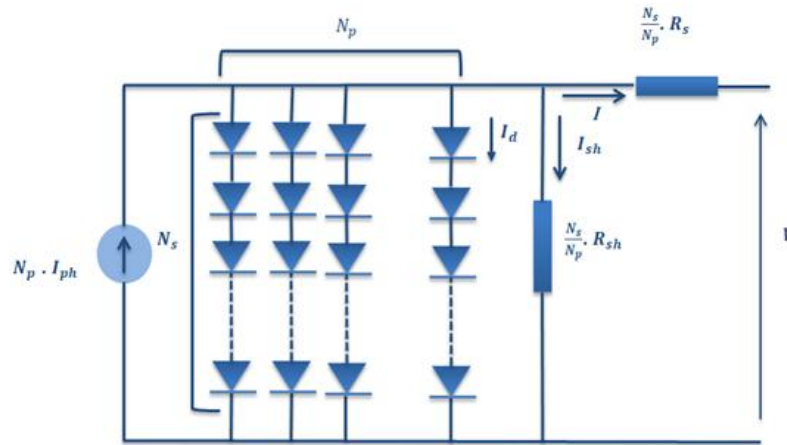


Figure 2. A circuit-based electrical model used to represent an actual PV panel

Table 3. Solar system specifications at STC conditions

Parameter specification	1STH-215-P	PV Array ($N_p=47$; $N_s=10$)
Maximum power at MPP (W)	213.15	100180
Voltage at MPP (V)	29	290
current at MPP (A)	7.35	345.45
Open-circuit voltage (V)	36.6	366
Short-circuit current (A)	7.84	368.48

2.2. DC-DC boost converter

To ensure that the photovoltaic array continuously operates at its maximum power point, a DC–DC boost converter is employed between the PV generator and the DC load [17]. The boost topology is selected due to its capability to raise the PV voltage to the required DC bus level while allowing effective MPPT control. The boost converter consists of an input capacitor, a controlled semiconductor switch, an inductor, a diode, and an output capacitor [18] as shown in Figure 3. The converter is controlled using a PWM signal with a constant switching frequency and an adjustable duty ratio. Varying the duty cycle changes the boost conversion ratio, thereby moving the PV operating point along the I–V characteristic. Under ideal steady-state assumptions, the boost converter input–output voltage relation is given in (5). This relationship highlights the direct influence of the duty cycle on power transfer and voltage regulation.

$$V_{out} = \frac{V_{in}}{1-D} \quad (5)$$

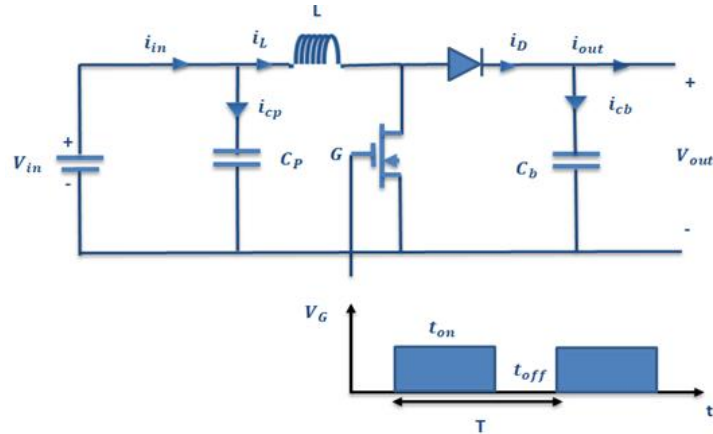


Figure 3. DC-DC power conversion stage

2.3. Perturb and observe (P&O) MPPT algorithm

The P&O method is commonly adopted for maximum power point tracking because of its straightforward structure and minimal computational requirements. It operates by introducing a small perturbation in the PV operating voltage or converter duty cycle and observing the resulting change in output power [26]. If a perturbation leads to an increase in power, the algorithm keeps applying the perturbation in the same direction, indicating movement toward the maximum power point. Conversely, if the measured power drops, the perturbation is applied in the opposite direction. As a result, the operating point repeatedly moves back and forth and, in steady state, fluctuates around the MPP, as illustrated in Figure 4. The P&O algorithm adjusts the duty cycle (D) of the DC–DC converter to maximize the PV array's output power, as shown in Figure 5.

At each sampling instant (k), the instantaneous power $P(k)$ is obtained from the measured voltage and current, and the variations ΔP and ΔV from the previous step.

- If $\Delta P > 0$, the duty cycle is adjusted in the same direction.
- If $\Delta P < 0$, the duty cycle direction is reversed.
- If $\Delta P = 0$, the duty cycle remains unchanged.

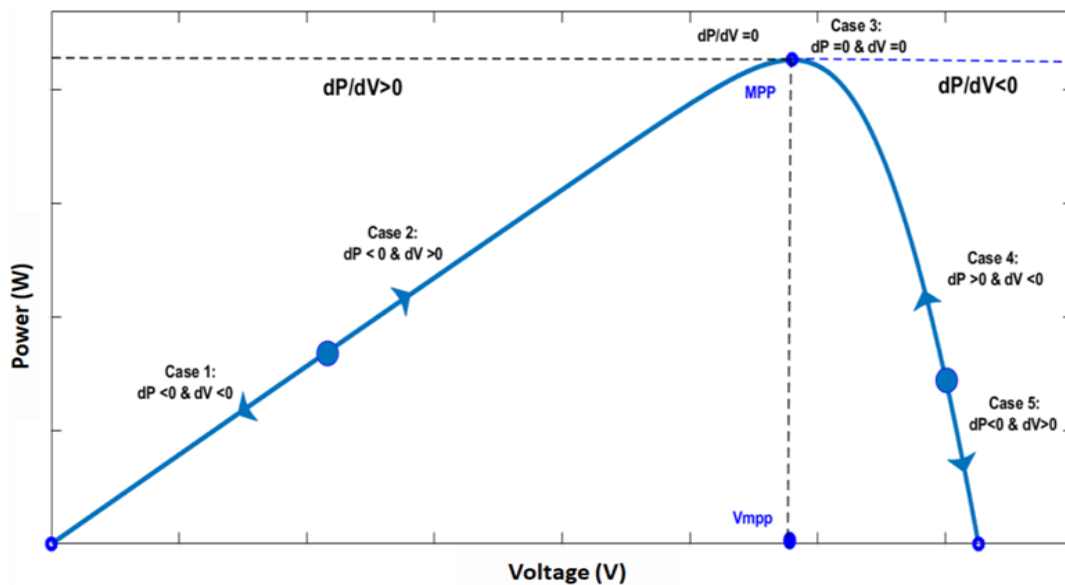


Figure 4. Perturb and observe algorithm

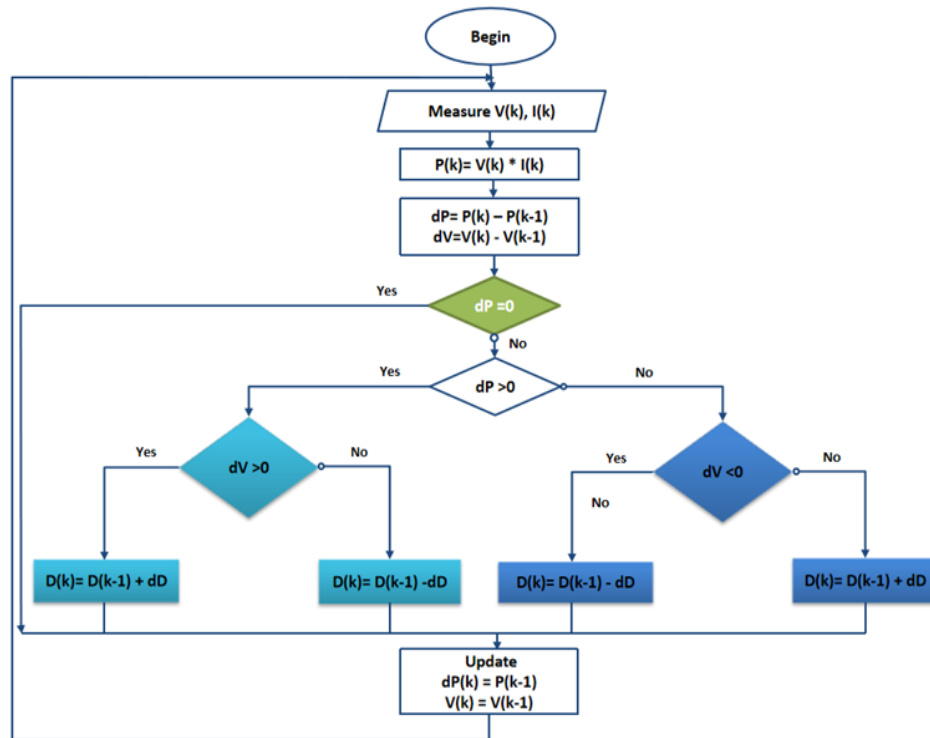


Figure 5. Perturb and observe the flowchart

2.4. Incremental conductance method

The INC approach enhances maximum power point tracking by relying on the theoretical criterion that the slope of the power–voltage characteristic becomes zero at the maximum power point. This condition is evaluated by comparing the incremental conductance (dI/dV) with the instantaneous conductance ($-I/V$), allowing the controller to accurately identify the position of the operating point relative to the MPP. In contrast to the Perturb and Observe technique, the INC algorithm is capable of significantly reducing steady-state oscillations and achieving faster tracking when irradiance varies rapidly. The fundamental operating principle of the INC method is illustrated in Figure 6, while the corresponding control flowchart is provided in Figure 7.

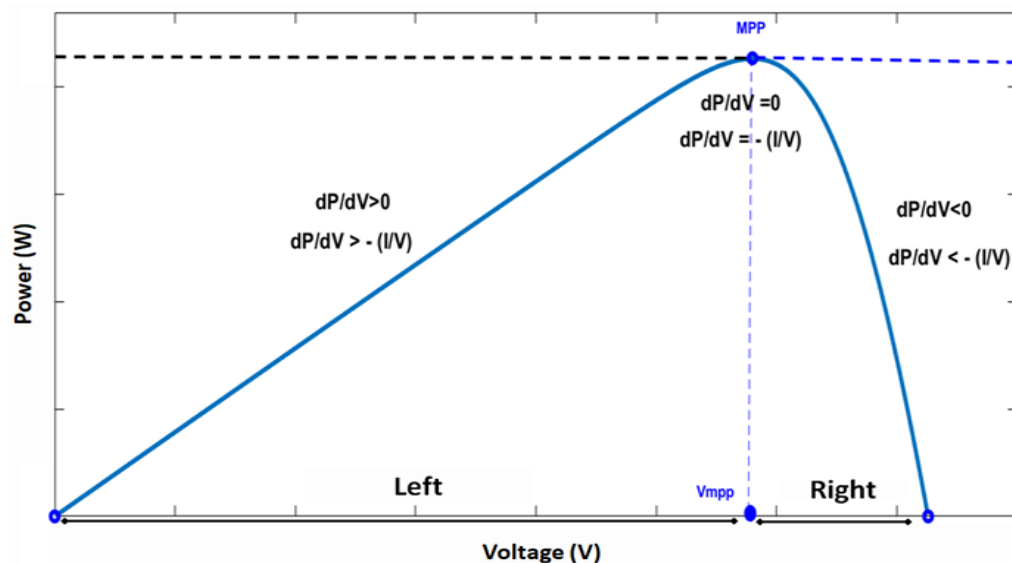


Figure 6. Incremental conductance algorithm

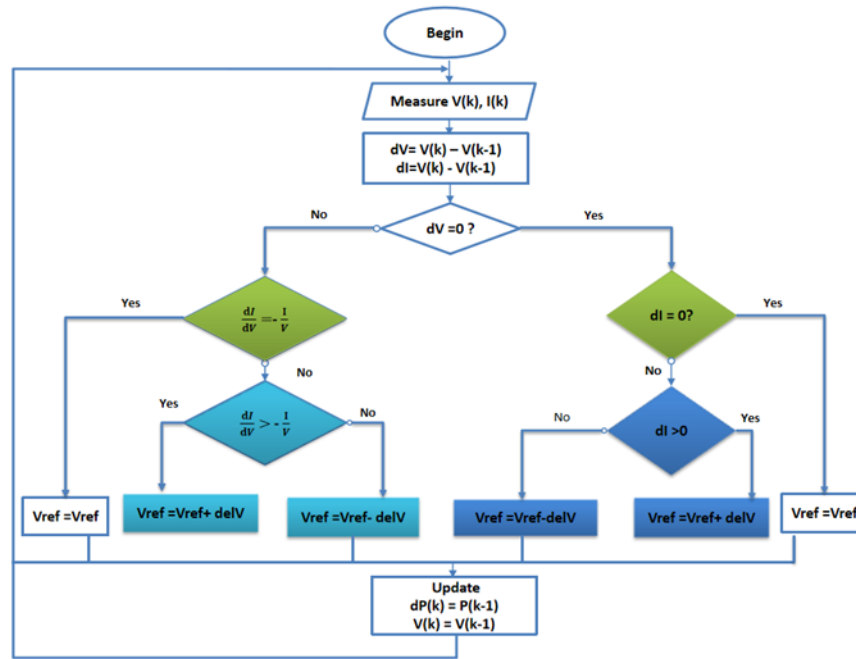


Figure 7. Incremental conductance flowchart

2.5. Comparative evaluation criteria

To ensure a fair and systematic comparison between the P&O and INC algorithms, both techniques are tested under identical simulation conditions. The evaluation focuses on three key performance indicators: tracking speed during irradiance variations, steady-state oscillations around the MPP, and tracking accuracy expressed in terms of power loss. Different irradiance and temperature profiles are applied to assess both steady-state and dynamic performance. This comparative methodology provides a clear basis for analyzing the strengths and limitations of each MPPT technique and supports informed decision-making for practical PV system design.

3. RESULTS AND DISCUSSION

3.1. Photovoltaic output characteristics

The operating characteristics of PV systems are strongly influenced by external conditions, particularly solar irradiance and cell temperature. To investigate their impact, these parameters were independently adjusted while maintaining Standard Test Conditions (25 °C and 1000 W/m²). The resulting I–V and P–V characteristics at 25 °C are illustrated in Figure 8. An increase in irradiance leads to a pronounced rise in output current, whereas the corresponding voltage variation remains relatively limited. Consequently, the maximum power output increases with irradiance, which is consistent with the fundamental behavior of photovoltaic devices.

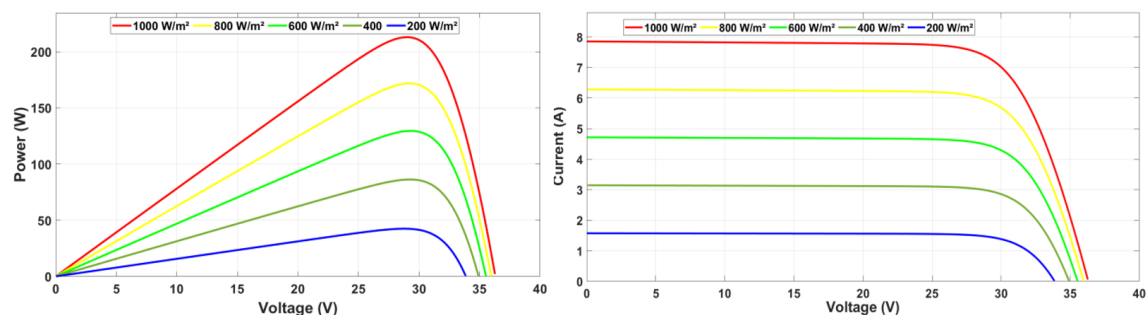


Figure 8. P–V and I–V curves for different irradiance levels at constant temperature

Figure 9 illustrates the impact of temperature variation on the (I-V) and (P-V) characteristics of the PV array under a constant irradiance of 1000 W/m^2 . With increasing temperature, the output current exhibits a slight rise, whereas the voltage decreases notably, leading to a reduction in maximum power. These behaviors are consistent with results reported in [15], [22]. The PV array comprises 740 modules (1STH-215-P) configured in 47 parallel strings, each containing 10 series-connected panels, as shown in Figure 10.

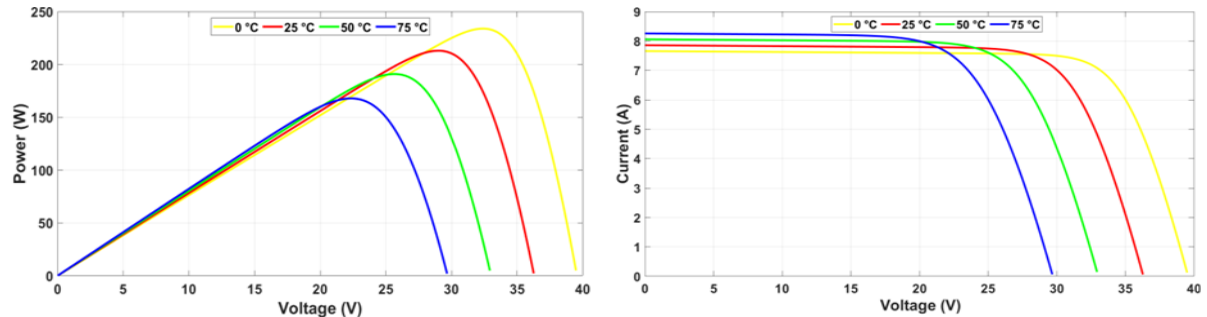


Figure 9. P-V and I-V curves for different temperature levels at constant irradiance

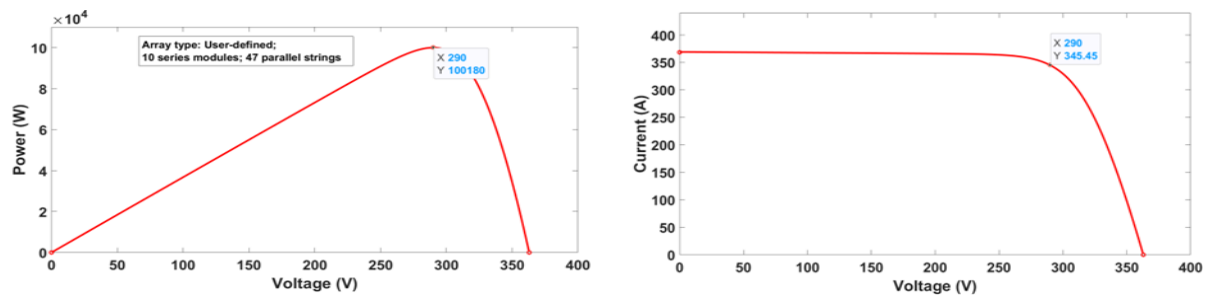


Figure 10. P-V and I-V characteristics of the proposed PV system under standard test conditions (STC)

3.2. Output of MPPT algorithms

Figure 11 shows the overall MATLAB/Simulink representation of the photovoltaic system, where a DC-DC boost converter interfaces the PV array with the load. The model integrates an MPPT control unit that can be configured to operate using either the P&O or the INC algorithm, depending on the selected MPPT technique.

3.3. Perturb and observe (P&O) algorithm output

The P&O method is noted for its straightforward design and implementation simplicity. However, as illustrated in Figure 12, it is prone to accuracy limitations due to its inherent oscillatory behavior around the MPP. These oscillations can result in continuous deviations of the operating point, particularly under rapidly changing environmental conditions, as noted in [6], [23].

3.4. Incremental conductance output

Figure 13 presents the tracking behavior of the INC algorithm, highlighting its effectiveness in tracking the maximum power point with higher accuracy. By jointly evaluating voltage and current variations, the algorithm adapts efficiently to rapid changes in irradiance and temperature. Consequently, this control strategy improves overall system stability and effectively suppresses oscillations around the maximum power point [23].

The simulation outcomes indicate that the INC algorithm consistently outperforms P&O under dynamic irradiance conditions. Similar trends have been reported in recent MPPT studies, where INC demonstrated superior stability due to its reliance on the incremental conductance condition ($dP/dV = 0$). However, the present work extends these findings by providing a quantitative comparison as shown in Table 4 using a large-scale PV array under identical operating conditions. From a practical perspective, these results indicate that P&O remains suitable for small-scale or cost-sensitive PV systems operating under relatively stable conditions, while INC is more appropriate for grid-connected or large-scale PV installations where rapid irradiance variations and efficiency optimization are critical.

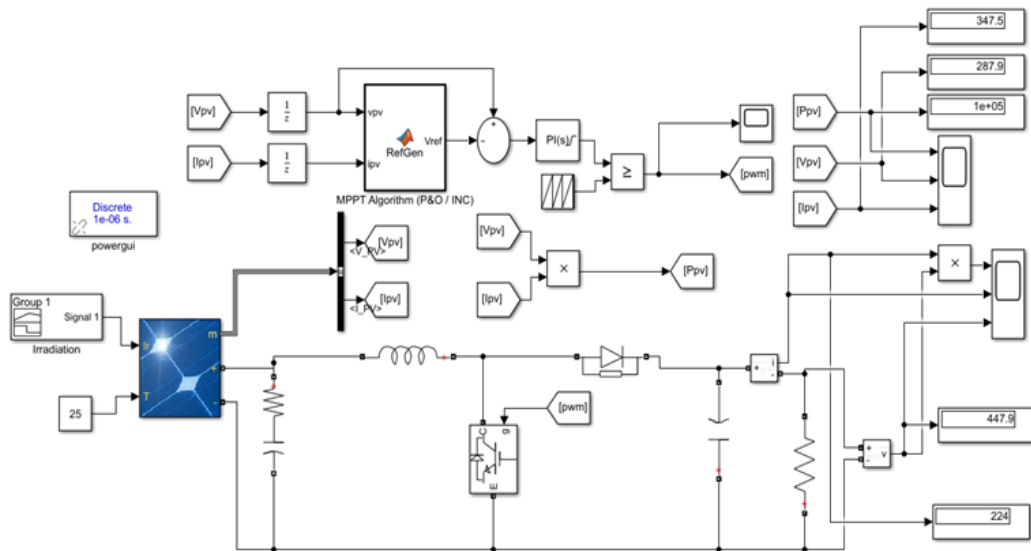


Figure 11. MATLAB/Simulink blocks of PV system with MPPT algorithm

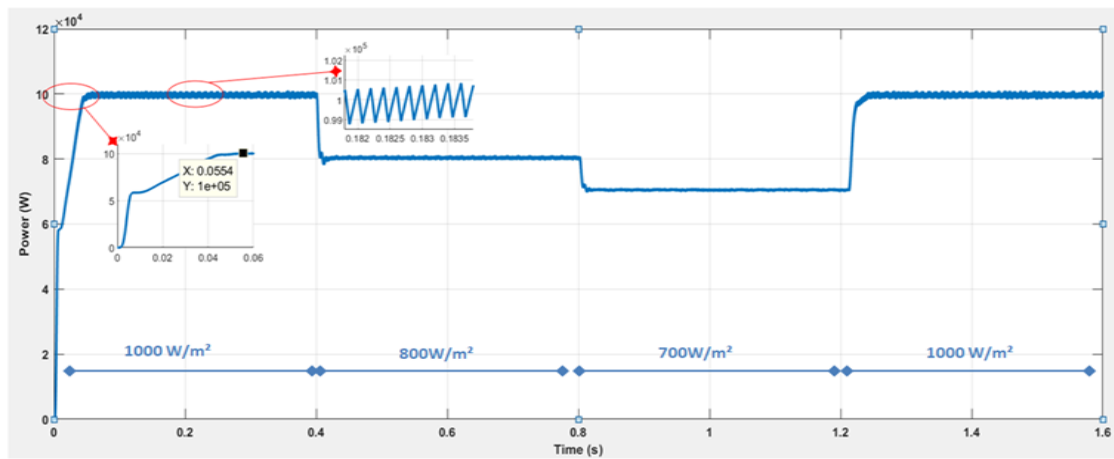


Figure 12. P&O MPPT response under irradiance variation, showing steady-state oscillations around the MPP

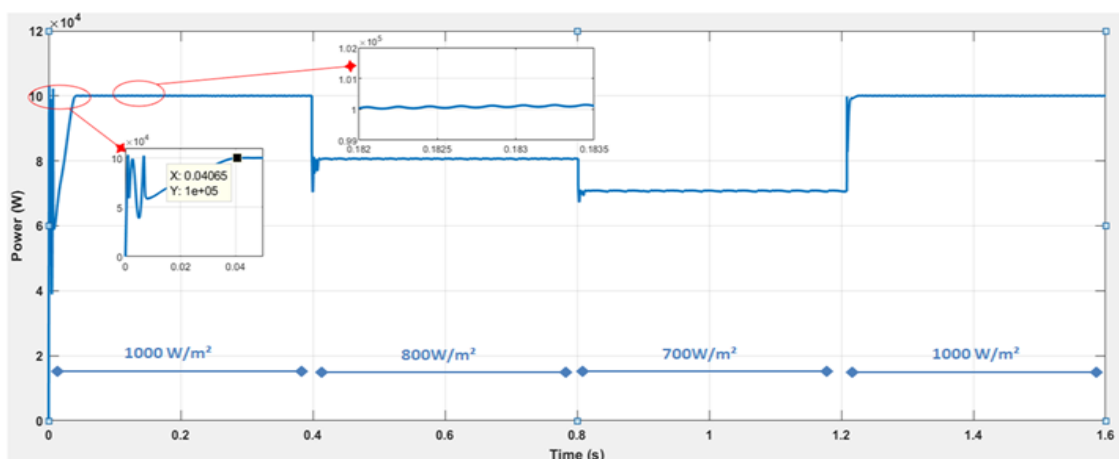


Figure 13. The INC MPPT response under irradiance variation showing fast convergence and stable MPP tracking

Table 4. Comparative evaluation of the P&O and INC MPPT algorithm

Criterion	Perturb & observe (P&O)	Incremental conductance (INC)	Remarks
Tracking speed	Moderate; ≈ 0.055 s convergence	Faster; ≈ 0.041 s convergence	INC $\approx 35\%$ faster
Precision at MPP	Moderate; visible oscillations ($\approx 3\%$)	High; minimal ripple ($\approx 1\%$)	INC achieves smoother tracking
Energy yield	$\approx 98\%$ of theoretical max	$\approx 99\text{--}99.5\%$	$\approx 1\text{--}2\%$ higher for INC
Dynamic performance	May lose MPP under fast irradiance variation	Stable under rapid changes ($dP/dV = 0$ criterion)	INC is more robust to fluctuations
Steady-state behavior	Oscillatory	Stable	INC shows reduced oscillation amplitude
Implementation	Simple; fewer computations (ΔP , ΔV)	More complex; requires dI/dV and I/V calculations	P&O simpler; INC heavier processing
Complexity			
Robustness	Reliable under steady conditions	Excellent under dynamic conditions	INC more resilient
Cost/hardware requirement	Low-cost, small PV systems	Large-scale, high-precision PV systems	Depends on system scale

4. CONCLUSION

This work provides a simulation-based investigation analysis of two conventional maximum power point tracking techniques, namely P&O and INC, applied to a photovoltaic system using MATLAB/Simulink. The results indicate that although the P&O approach is characterized by a simple structure and low computational demand, it suffers from steady-state oscillations and reduced tracking accuracy under dynamic operating conditions. In contrast, the INC algorithm achieved a faster convergence time (approximately 0.041 s compared to 0.055 s for P&O), exhibited significantly lower oscillations (around 1%), and provided an efficiency improvement of about 2–4%. These quantitative outcomes support the selection of INC for photovoltaic systems exposed to rapid irradiance variations, while P&O remains suitable for applications operating under relatively stable conditions. Future work will focus on experimental validation and the development of hybrid MPPT strategies combining conventional approaches with intelligent optimization techniques to further enhance photovoltaic system performance.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization

M : **M**ethodology

So : **S**oftware

Va : **V**alidation

Fo : **F**ormal analysis

I : **I**nvestigation

R : **R**esources

D : **D**ata Curation

O : Writing - **O**riginal Draft

E : Writing - Review & **E**ditng

Vi : **V**isualization

Su : **S**upervision

P : **P**roject administration

Fu : **F**unding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The simulation data that support the findings of this study are available from the corresponding author upon reasonable request.

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